Saturated conductivity and effective porosity of the forest soil[1]

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Abstract Soil samples were taken from different soil depth of different forest soil story in the Natural Reserve of Changbai Mountain, and their saturated conductivity and effective porosity were measured. The variation of saturated conductivity and effective porosity with different soil depth were studied by regressive analysis and a logarithmic model. The results were compared with the exponential model (Beven 1982). The results of comparison showed that the logarithmic model was more accurate and reasonable than the exponential model for forest catchment.
Key words: Saturated conductivity, Effective porosity, Logarithmic model

Introduction

Effective porosity is designated according to the difference of saturated volumetric water content and residual volumetric water content ($\omega=\theta_s-\theta_r$). Saturated hydraulic conductivity and effective porosity are two important parameters in model and simulation of subsurface flow. Moreover, people can seek the unsaturated conductivity by joining the two parameters with models of conductivity (Mualem 1976; Brook & Corey 1964). Therefore, the study about these two parameters is extremely useful for exploring the regulations of water flow in saturated and unsaturated zone in irrigation or drainage, civil engineering, water conservancy project and hydrological calculation. Many studies on saturated conductivity and effective porosity have been carried out, and some models of saturated hydraulic conductivity have been presented in previous papers (Pei Tiefan 1981; Beven *et al*, 1982; Smith & Dikkrugger 1992). But, most of these models could only be used to estimate the ensemble mean value of saturated conductivity in entire soil profile. In most previous studies of infiltration of soil water, saturated conductivity and effective porosity were taken as fixed values in the entire soil profile and replaced by their equivalent values respectively. In fact, these equivalent values are the ensemble mean values in entire soil profile and evaded the factors of soil heterogeneity and soil structure. Many studies of infiltration have shown that the saturated conductivity and effective porosity do not vary with soil depth is only reasonable under strict condition, such as steady flow (Bresler & Dagan, 1983; Smith & Freeze, 1979; Smith *et al*, 1996). Beven (1982) has pointed out by many studies at field that both saturated conductivity and effective porosity decreased with soil depth. It must lead to greater error in simulation of soil water flow to regard these parameters as fixed values and to replace them with their equivalent values. There have been no suitable models expressing the variation of saturated conductivity and effective porosity with soil depth in forest cacthment yet.

In this paper, a mathematical model of variation of saturated conductivity and effective porosity with soil depth, was established by regression analysis with high precision, and based on the experimental results from different forest soil in National Reserve of Changbai Mountain. It would provide a useful scientific foundation for hydrological calculation of cacthment, forecasting of flood, soil and water conservation, and pollution of environment and rational utilization of water.

Methods and site

Study site

The experimental field was set up in National Reserve of Changbai Mountain of Erdao Baihe River forest catchment. Erdao Baihe River acrosses the reserve from south to north, and is the source of Songhua River. The Nature reserve is located in the southeast of Jilin Province of China at approximately longitude (128°05'E) and latitude (42°01'N). The primitive forest area is about 210000 hm^2, the region is called "Changbai Forest Sea", in which *Pinus koraiensis* is the main component. Besides *Pinus koraiensis*, there are *Picea jezoensis, Abies nephrolepis, A. holophylla, Tilia amurensis, Quercus mongolica, Fraxinus mandshurica, Ulmus and Betula,* they form mixed conifer-broad-leaved forest and make up the main forest types in the region. The annual mean precipitation is about 600~900 mm and the highest is 1340 mm in north of the Yangtze River. The biological resources in the region are rich. Vertical zonality of vegetation distribution from the top to the foot of the mountain ranges for *Betula ermanii* forest, dark coniferous forest, *Pinus sylvesfriformis* forest, *Larix olgensis* forest and broad-leaved Korean pine forest. The main soil types from the top to the foot of this mountain are mainly divided into four types, such as mountain tundra soil, mountain sod forest soil, brown coniferous forest soil and dark brown forest soil. Both the dark brown forest soil (plot No.1) and the mountain brown coniferous

[1] The project was funded by the Opened Research Station of Changbai Mountain Forest Ecosystem, Chinese Academy of Sciences.

forest soil (plot No. 2) are selected as experimental soil fields. The characteristics of the two plots are given as follows.

In Plot No.1, Attitude is 600~1000 m, mean slope gradient (2%~4%) is comparatively even and flat. The soil is predominated by clay soil. The vegetation is consisted of broad-leaved Korean pine, which is the main tree species in the plot, such as *Tilia amurensis, Fraxinus mandshurica, Betula costata,* and so on. There is high activity of soil organisms. The typical soil profile is given in Table 1.

Table 1. The typical soil profile of dark-brown forest soil (in plot No.1)

Depth /cm	Horizon	Description
0~4	L	Litter
4~6	F	Semi-decomposed litter
6~11	Ah	Dark gray humus and sticky loam, scattered structure, the color of soil varies obviously with depth, many roots
11~30	Aw	Light gray fine sticky loam, aboundant roots, but quantity of roots decreased obviously with depth
30~50	AwB	Dark gray alibi soil, fewer roots
50~105	C	Dark gray clay, mottles, very moist, blocky structure, rare roots

In Plot No. 2, Altitude is 1100~1800m, and the mean slope gradient is 5%~8%. The soil predominated by sandy loam is mainly derived from volcanic ash, with some volcanic gravel in some parts. Most river valleys cut by river are shown as "U" pattern. Grass covering rate is about 40%, and the forest is mainly made up of *Picea jezoensis* and *Picea koyamai*. Besides the two tree species, there are *Abies nephrolepis, Betula ermanii* and *Larix olgensis*. The typical soil profile is given in Table 2.

Table 2. The typical soil profile of brown coniferous forest soil (in plot No. 2)

Depth /cm	Horizon	Description
0~3	L-H	Litter
3~7	Ah	Humus, dark brown fine sandy soil, crappy granular structure, many roots
7~15	Ae_2	Light gray gravel-sandy soil, with white fungus trace, many roots
15~55	Bfh	Dark brown gravel-sandy soil, with a few deposited iron and humus, many roots and quantity of roots decreased with depth
55~95	BC	Dark brown gravel-sandy soil, color of soil is lighter than Bfh layer, rare roots
95~135	C	Brown gravel-sandy soil, with gravel, no roots

Experimental methods

The sampling slope was selected as in plot No.1 and in plot No. 2 respectively. The sampling slopes had better vegetation cover, and the well-distributed gradient represent that of experimental field. The soil of sampling slope was not destroyed by human being. Then, sampling sites (1~2) were arranged randomly and separately from upper to lower position in each sampling slope. In each sampling site, soil sample with litter being moved away, was taken at different soil depth interval about 10 cm (soil depth from 0 to 100 cm). At the same time, we numbered each soil sample, and recorded the soil type, position of slope, number of sampling point and the soil depth of sample. The depth of center of soil sample was taken as the soil depth of the sample. Then, saturated conductivity was measured by fixed hydraulic head instrument. The residual volumetric water content and saturated volumetric water content were measured by weighing method in Forest Hydrological Modeling Laboratory. The effective porosity of soil sample can be calculated by the formula:

$$\omega=\theta_s - \theta_r$$

Where ω is effective porosity of soil; θ_s is saturated volumetric water content of soil; θ_r is residual volumetric water content of soil.

Based on average saturated conductivity measured in the same soil depth from upper to lower slope in each sampling slope, we established a saturated conductivity model and an effective porosity model respectively.

Results and analysis

According to the method introduced above, we measured values of saturated conductivity and effective porosity of each soil sample, and obtained regression relations of saturated conductivity and effective porosity varying with soil depth in plot No.1 and plot No. 2 (Table 3~6 and Fig. 1~2). These results of both saturated conductivity and effective porosity decrease logarithmically with soil depth. All the correlation coefficients are greater than 0.9, The common form of these regression equations can be expressed as:

$$K_s(z) = K_0-f_1\ln z \qquad (1)$$

$$\omega(z) = \omega_0-f_2\ln z \qquad (2)$$

Where ω_0, $\omega(z)$ is effective porosity on surface and at the soil depth of z, respectively; K_0, $K_s(z)$ is saturated conductivity on surface and at the soil depth of z; z is depth of soil; f_1, f_2 are constant terms.

Then a general logarithmic model of saturated conductivity and effective porosity varying with forest soil depth can be given as following:

$$K_s(z) = K_0-f_1\ln a_1 z \qquad (3)$$

$$\omega(z) = \omega_0-f_2\ln a_2 z \qquad (4)$$

Where a_1, a_1 are constant terms and their units are reciprocal with that of soil depth z, e.g. $a_1=a_2=1cm^{-1}$ when the unit of z is cm, and equations (3) and (4) could be simplified as equations (1) and (2), respectively.

Table 3. Values of saturated conductivity in plot No.1

Depth /cm	K_sx10^{-4} / cm • s^{-1} Upper slope	Lower slope	Mean values
2	1.69000	1.6400	1.66000
9	1.30000	1.3300	1.32000
11	1.24000	0.8200	1.03000
17	0.76000	0.6800	0.72000
22	0.55000	0.5000	0.52000
26	0.40000	0.3900	0.40000
32	0.34000	0.3500	0.34000
38	0.33000	0.3200	0.32000
51	0.00100	0.0008	0.00090
56	0.00048	0.0005	0.00049

Note: K_s is saturated conductivity.

Table 4. Measured values of saturated conductivity in plot No. 2

Depth /cm	K_sx10^{-4} / cm • s^{-1} Upper slope	Lower slope	Mean values
2	3.91	4.05	3.98
13	2.45	2.98	2.71
22	2.00	2.18	2.09
32	1.69	1.77	1.73
42	1.58	1.52	1.55
52	1.56	1.30	1.43
62	1.47	1.09	1.28
72	1.22	1.28	1.25
82	1.00	1.08	1.04
92	0.73	0.95	0.84

Note: K_s is saturated conductivity.

Table 5. Measured values of effective porosity in plot No.1

Upper slope		Lower slope		Mean values	
Depth /cm	ω %	Depth /cm	ω %	Depth /cm	ω %
1.5	17.20	1.5	21.55	1.5	41.14
16.5	8.19	8.5	8.08	9.5	19.69
21.5	7.88	15.5	8.29	15.5	7.98
31.5	7.77	25.5	7.25	22.5	9.22
37.5	6.63	31.5	7.56	29.5	7.77
43.5	6.84	38.5	6.94	36.5	7.36
50.5	6.22	50.5	6.01	47.5	6.94
55.5	7.87	57.5	6.94	57.5	5.28
		63.5	6.94	70.5	4.56
		63.5	3.42		

Notes: ω is effective porosity.

Since Beven (1982) put forward an exponential model of saturated conductivity and effective porosity varying with soil depth, we compared our logarithmic model with the exponential model by the measured (Fig. 1~2).

Conclusions and Discussion

The results of comparison show that the logarithmic model is better than the exponential model, which has high precision, accuracy and vast application.

Table 6. Measured values of effective porosity in plot No. 2

Depth /cm	ω % Upper slope	Lower slope	Mean values
1.5	40.45	42.90	41.68
12.5	32.09	35.95	34.02
21.5	29.31	34.61	31.96
31.5	22.8	33.53	33.16
41.5	23.11	29.12	26.11
51.5	22.7	26.73	24.71
61.5	20.12	27.04	23.56
71.5	20.65	27.87	24.26
81.5	20.84	26.73	23.78
90.5	19.90	26.21	23.10

Notes: ω is effective porosity.

In forest catchment, the upper soil story has a large saturated conductivity and effective porosity, due to humus concentration activity, frequent activity of soil organism, decayed root holes, animal burrows, and worm holes. All these factors obviously decrease with soil depth, saturated conductivity and effective porosity also decrease obviously with soil depth. Because saturated conductivity of clay soil itself is very little in forest intensive clay soil (such as in plot No.1), it is difficult for humus to move down to deeper soil. And soil animals and roots of vegetation hardly reach deeper soil. Saturated conductivity in the deeper soil may be 1or 2 orders of magnitude, and less than that of surface. In the case that exponential model is used for saturated conductivity in such a clay soil, it must lead to greater regression values of saturated conductivity of surface (K_0) and decay coefficient (f) with the smallest regression error. Therefore, regression values of saturated conductivity in upper soil are obviously greater than their measured values (Fig. 1. A.~C.).

On the contrary, since effective porosity in the deeper soil is only several times less than that of surface. In such a clay soil, regression values of effective porosity with gently the regression curve calculated by the exponential model are obviously less than that of measured values (Fig. 2.A.~C.). But, as for in forest sandy soil (such as in plot No. 2), because saturated conductivity and effective porosity of sandy soil are much greater than that of clay soil, their dissimilarities between surface and deeper soil are much less than that in clay forest soil. In the case that exponential model is used in forest sandy soil, regression values of saturated conductivity and effective porosity in upper soil, with gentle regression curve, are obviously less than their measured values (Fig.1. D.~F. and Fig.2. E.~F.). Generally, the application of the exponential model is limited while the logarithmic model is well used in forest clay soil. And the precision of the logarithmic model is higher than that of the exponential model in forest sandy soil, too. The logarithmic model, with vast application and high precision, is reasonable in forest soil.

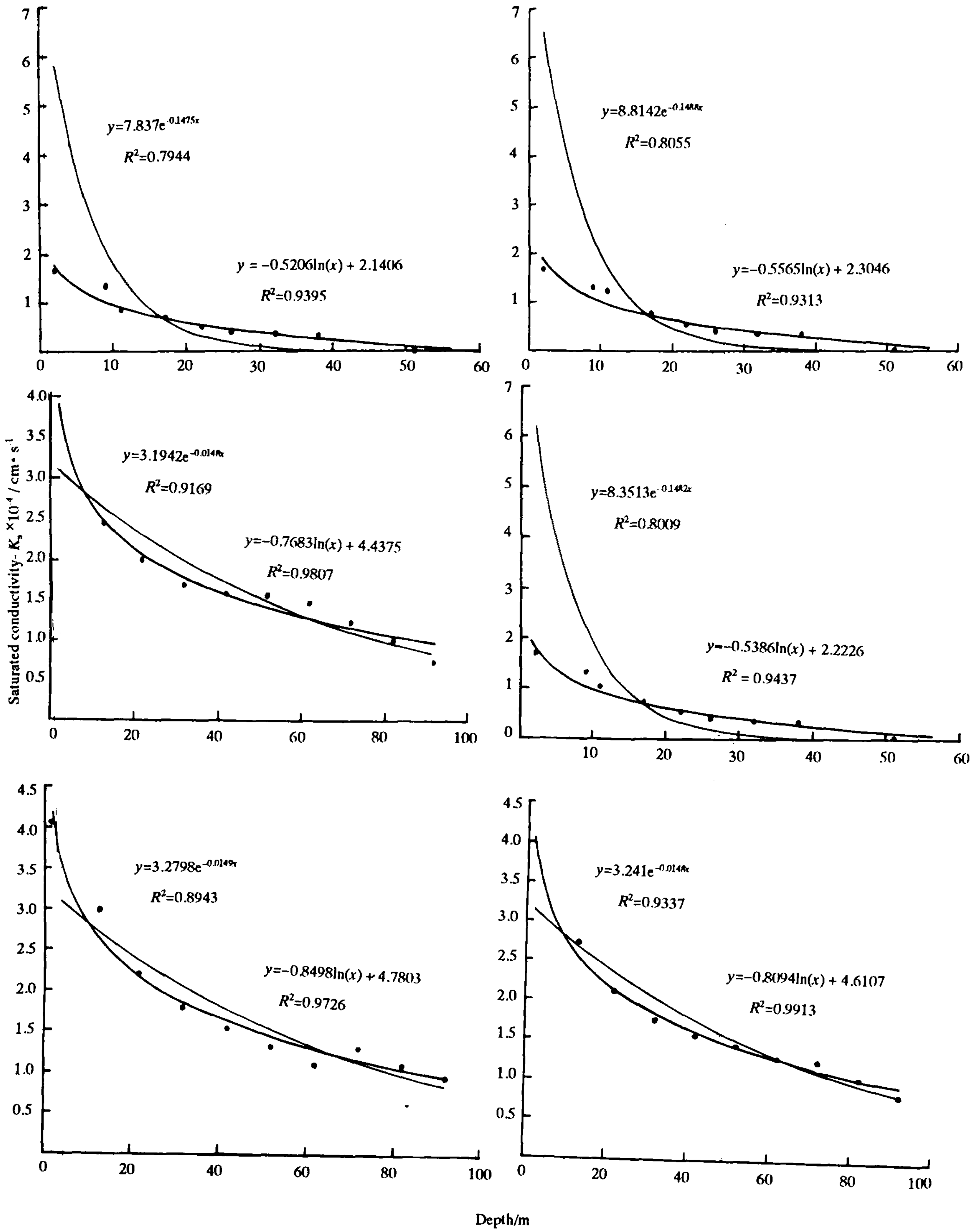

Fig. 1. Models of saturated conductivity.

A. Model of saturated conductivity at upper-slop in plot No. 1; B. Model of saturated conductivity at lower-slop in plot No.1; C. Model of mean saturated conductivity in plot No. 1; D. Model of saturated conductivity at upper-slope in plot No. 2; E. Model of saturated conductivity at lower-slope in plot No. 2; F. Model of mean saturated conductivity in plot No.2·

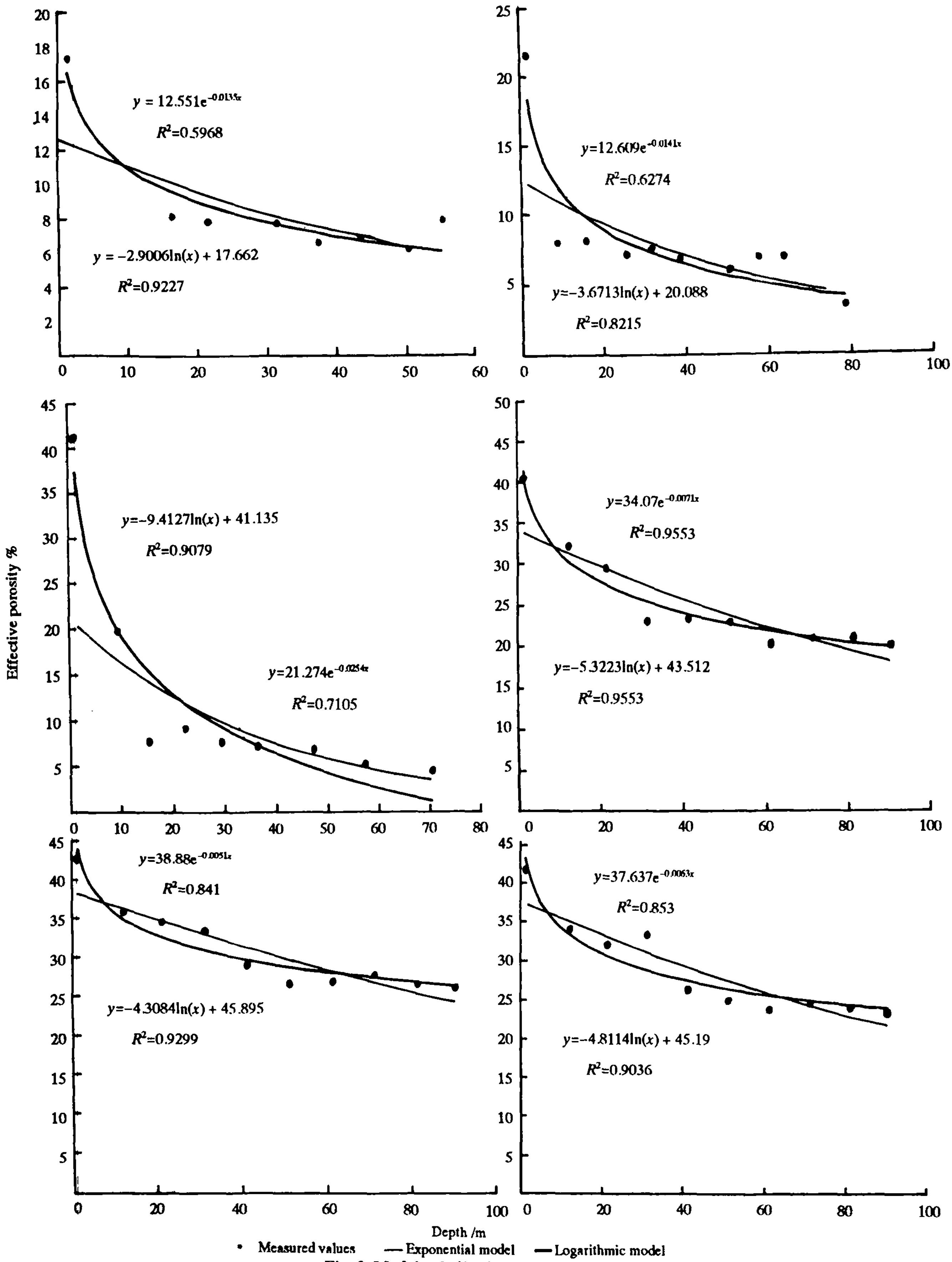

Fig. 2. Models of effective porosity

A. Model of effective porosity at upper-slope in plot No. 1; B. Model effective porosity at mid-slop in plot No. 1; C. Model of effective porosity at lower-slope in plot No. 1; D. Model of effective porosity at upper-slop in plot No. 2; E. Model of effective porosity at lower-slope in plot No.2; F. Model of mean effective porosity in No.2 field.

Although the variation of experimental condition is large, for example, the soil changed from clay soil to sandy loam soil and the vegetation changed from coniferous forest to broad-leaved forest, the regulations of saturated conductivity and effective porosity decreasing logarithmically with soil depth were still consistent. The present logarithmic model would be a universal law of saturated conductivity and effective porosity in forest catchment. On another occasion, two points are worth: 1). The measured values of saturated conductivity and effective porosity of each soil sample in our experiment are not really the values of the depth of the center of corresponding soil sample, but also the average values of corresponding soil sample. Since the 4cm length of soil samples is much smaller than the total sampling soil depth which is about 100 cm, it is completely reasonable to regard the soil sample as a point in the entire depth of soil profile. 2). We can find from equation (1) and (2) that the values of saturated conductivity and effective porosity computed by the model (z<1cm) are greater than K_0 and ω_0, which is obviously unreasonable. So we must have our models for K_s (z)=0 , z<1cm and ω (z)=ω_0 (z<1cm). It means that saturated conductivity and effective porosity of soil depth z (z<1 cm) are equal to that of surface separately. The depth of soil profile in forest is generally much greater than 1 cm, so it is completely reasonable and do not affect the value of use of the model. The soil layer is regarded (z<1cm) as the surface of soil profile.

According the experiment, we could conclude:

1. The saturated conductivity of soil decreases logarithmically with soil depth in forest catchment.
2. The effective porosity of soil decreases logarithmically with soil depth in forest catchment.
3. The law of saturated conductivity varying with soil depth is consistent with that of effective porosity varying with soil depth in forest catchment.
4. The logarithmic model presented in this paper is more conformable in actual situation than the exponential model presented by Beven (1982) in forest catchment.

Acknowledgements

This paper was part of the project of Simulation and Model of Interflow on Hillslope of Forest Catchment , which was funded by the National Natural Science Foundation of China, Chinese Academy of Sciences and Science and Technology Commission of Liaoning Province. The experiment would not have been conducted possible without the enthusiastic support of Changbai Mountain Station, Chinese Academy of Science. We thank Shen Yanli of Tsinghua University, Liu Shijun of Shenyang Agriculture University and Chen Lihua of Beijing Forestry University for their enthusiastic helps.

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(**Responsible editor**: Zhu Hong)